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Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10/16/92	Quarterly Progress Report R&D Status Report 7/01/92 - 9/30/92

4. TITLE AND SUBTITLE R&D Status Report: Quarterly Progress Report #4 RF Vacuum Microelectronics	5. FUNDING NUMBERS MDA972-91-C-0030
6. AUTHOR(S) D. K. Arch	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Honeywell Sensor and System Development Center 10701 Lyndale Avenue South Bloomington, Minnesota 55420	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Advanced Research Projects Agency DARPA/DSO 3701 N. Fairfax Arlington, Virginia 22203	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We summarize our fourth quarter progress towards developing a thin film edge emitter vacuum triode capable of 1 GHz modulation for sustained (>1 hour) periods of time. Current densities of up to 10 μA/μm have now been measured on diode structures. Total current emission of 380 mA was measured for a thin film edge emitter diode which is a factor of 25 greater than at the start of the program. A diode array structure was designed to demonstrate the program requirements of 5 mA total current. This array is now in process. The thin film ordered this quarter and the first fabrication run is completed and now test.

14. SUBJECT TERMS Vacuum microelectronics, edge emitter, triode, high frequency devices	15. NUMBER OF PAGES 7
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

R&D Status Report
RF Vacuum Microelectronics
Quarterly Progress Report #4
(7/1/1992 - 9/30/92)

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Effective Date of Contract: September 30, 1991

Contract Expiration Date: March 31, 1993 (Baseline)

Contract Amount: Baseline $1,315,650

Option: $ 772,532

Principal Investigator: Tayo Akinwande 612/887-4481

Program Manager: David K. Arch 612/887-4404

Title of Work: **RF Vacuum Microelectronics**

I. Executive Summary

Technical Approach: Our technical approach is to utilize thin film technology and surface micromachining techniques to demonstrate an edge emitter based vacuum triode. The edge emitter triode approach offers several potential advantages to achieving high frequency device operation (compared to cone emitters or wedge emitters):

- The fabrication process is a planar process, compatible with most silicon IC manufacturing.
- Thin film processes for the films used in the triode process are well controlled and reproducible. Control of film thicknesses to within 5% for the emitter film thickness is easily attainable resulting in a well-controlled edge emitter.
- Device capacitance for the edge emitter is less than that achievable for cones or wedges resulting in potentially higher frequency operation.

Program Objective: **Demonstrate an edge emitter based vacuum triode with emission current density of 10 μA/μm at less than 250 V which can be modulated at 1 GHz continuously for 1 hour.**

Key Achievements (this reporting period)

- Demonstrated current densities of 10 μA/μm for a diode field emitter (at ~120V)
- Achieved a maximum current emission of 380 μA for a single diode edge emitter, a factor of 2.5 greater than reported last quarter and a factor of ~25 greater than at program start.
- Completed first triode field emitter process run. Devices presently are in test. Initiated second triode fabrication run.
- Designed diode array device to demonstrate total device emission current of 5 μA and 5A cm^{-2}. Initiated diode array fabrication run.
- Completed the fifth and sixth fabrication runs of diode field emitter devices to examine the influence of emitter material on device performance and to compare TaN and sputtered boron doped polysilicon resistors.

II. Milestone Status

	Completion Date: Planned	Completion Date: Actual (estimate)
1. Field Emitter Development		
Test Structure Design Complete	12/91	1/92 (complete)
Determine Workable Emitter Structure	3/92	3/92 (complete)
Demonstrate Emission Current of 10 μA/μm	11/92	11/92 complete
Deliver 10 Field Emitting Diodes	12/92	12/92 (on plan) (delivered 10/13/92)
2. Process Development		
High Resistivity Thin Film Resistor	4/92	9/92 (complete)
Complete Dielectric Studies	5/92	6/92 (complete)
Mechanical and Electrical FEM Analysis	5/92	8/92 (complete)
3. Triode Development		
-Triode Design Complete	4/92	5/92 (complete)
-Demonstrate Reliable/Uniform Current Emission	7/92	10/92
-Demonstrate Modulated/Edge Emitter Triode	8/92	11/92
-Demonstrate 1 GHz Modulation of Triode	2/93	12/92
-Deliver 2 Triodes	3/93	2/93
4. Final Report (Baseline)	4/93	4/93

III. Technical Progress

Efforts during this reporting period focussed on the following:

- Completion of the triode field emitter design and fabrication of the first triode devices.
- Design of an edge emitter diode array for achieving the 5 A cm^{-2} and 5 mA total current program objective.
- Fabrication of thin film emitter diodes to evaluate emitter material and thin film resistors.
- Extensive testing of field emitter diodes for current emission, emission uniformity, emission current behavior versus control voltage, etc.

Task 1. Field Emitter Development

Two additional field emitter diode fabrication runs (diode run #5 and #6) were completed this quarter (4 runs were completed last quarter). The primary objective of the runs were to study the influence of emitter material on the performances of the devices. The runs looked at TiW, WN_x, WSi_x, TaN, a TiW/WSi_x/TiW layered emitter and (Si,Ta)N_x cermet. A second objective of run #5 was to compare TaN and sputtered boron doped polysilicon resistors for device current limiters. Diodes from these runs are presently in testing.

Extensive testing was carried out this quarter on devices from the first four diode fabrication runs. With the field emitter diode structure we have measured the following device performance:

- Highest current ever reported for a single edge: 380 mA.
- Highest current densities reported for an edge emitter: 9.6 μA/μm.
- Long-term current emission: 50 mA emission from a single edge for greater than 70 hours.
- Current areal densities with similar performance to field emitter arrays based on Mo cones.
- Comb structure emitters with and without current equalization sense resistors.

Below is a summary of our best results to date obtained for different device sizes and materials:

Emitter Material: 300Å TiW

Device Width	Resistor	Maximum Current	Current Density
5 μm	No Resistor	48 μA	9.6 μA/μm
10 μm	No Resistor	59 μA	5.9 μA/μm
20 μm	No Resistor	165 μA	8.25 μA/μm
50 μm	No Resistor	288 μA	5.75 μA/μm
100 μm	No Resistor	383 μA	3.8 μA/μm

Emitter Material	Maximum Current	Maximum Current Density
TiW	380 μA	9.6 μA/μm
Pt	6 μA	0.6 μA/μm
Mo	10 μA	1 μA/μm
WSi_x	250 μA	7.8 μA/μm
WN_x	118 μA	9.1 μA/μm

As indicated by the dependence of burn-out current on edge-width, we can conclude that the emission current is not coming from the two corners of the edge, but rather from the length of the edge though it does not scale linearly.

We have also demonstrated repeatable diode-like IV characteristics with the edge emitter diode. The device has 5 μm wide fingers and 5 μm spaces and uses a 1MΩ/square resistor (TaN - developed earlier in this program) in each finger to serve as a current limiter.

We have also made changes to the diode mask set to fabricate field emitter diode arrays which will meet the 5 A cm^{-2} and 5 mA total current objective of the program. These arrays were designed based on the diode results achieved to date. The designs assume a 2 μA/μm emission current density to achieve the 5 mA total current goal. Devices are now in fabrication and are expected to be completed in mid October.

Task 2 Process Development

Several experiments were carried out to define the fabrication process for the vacuum triode device:

Comb definition: A critical step in the triode process is the definition of the comb emitter. At this point, we are etching both the emitter and the current limiting resistor. Since there is overlap between the emitter and the resistor it implies that there will be some region of the underlying nitride layer that will be exposed for longer times than others. We developed processes to have an etch stop such as ZrO and Al_2O_3 to prevent etching of the nitride.

Layered Emitter Structures: A process was developed for depositing Ti/TiW/Al layered emitter structures.

PECVD Oxide Sacrificial Layer: We have decided to change from BSQ to PECVD oxide for the sacrificial layer because of the faster etch rate of PECVD oxide (4,000Å/min for PECVD oxide vs. 500Å/min for BSQ.) The slower etch rate means that the nitride support layers of the emitter and the control layers are exposed to BOE for a longer period of time than is desirable. The substitution of PECVD oxide for BSQ means this nitride will not be exposed to such a long etch time.

Task 3 Triode Development

The thin film edge emitter triode design was completed at the beginning of this reporting period. Mask sets were ordered and the first fabrication run was completed in mid-September. The run had four emitter splits: (1) 200Å TiW emitter; (2) 400Å TiW; (3) 200Å WSi_x, and (d) 400Å WSi_x. Several issues were encountered during device fabrication which affected yield for this run. These issues have been addressed in process development tasks. As a result we have subsequently made the following changes in the triode process:

- The emitter layer support nitride thickness will be increased.
- The sacrificial etch layer was changed from BSQ to PECVD oxide.
- The nitride layer is now layered with two outer nitride layers which are resistant to buffered HF and inner layer of low stress nitride.
- The comb definition step and the emitter cap definition steps have ben revised to have proper inspection to prevent incomplete etching at critical steps necessary for the self alignment of the emitter to the control electrodes.

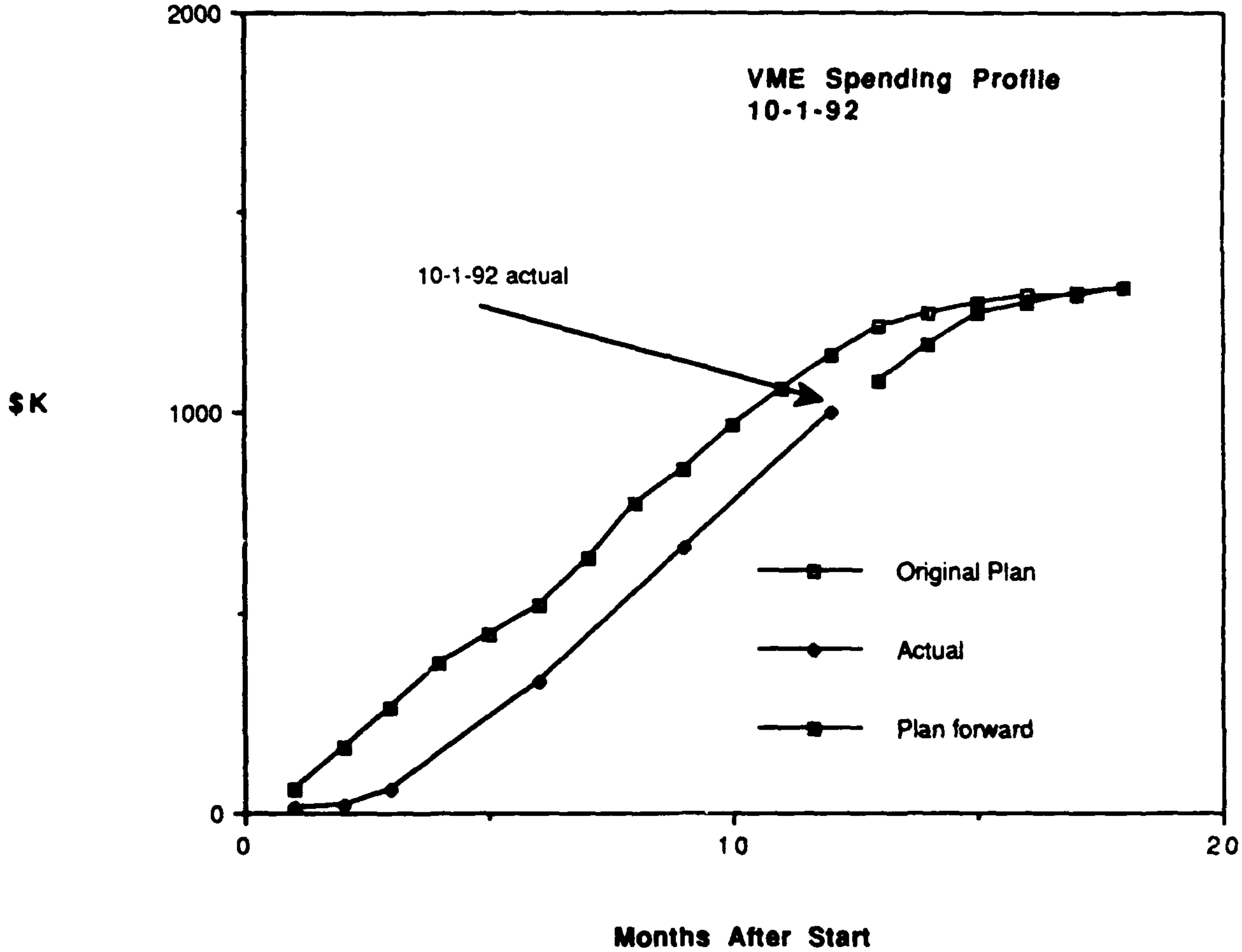
Two wafers from the first triode fabrication run have potentially working devices. They will be tested and evaluated in early October. We have started the second triode fabrication run, incorporating the above mentioned changes and expect to complete this run in early-to-mid November.

We continued our analysis of triode performance this performing period. Analysis of the triode equivalent circuit for the edge emitter triodes being processed currently show that we can expect 1 GHZ operation with some gain and that the gain will increase as the device geometry (namely, the control electrode-to-emitter spacing) is reduced. With the edge emitter configuration this spacing can be readily controlled. In addition, our analysis shows that if the current is limited by its density at the emitter surface we can expect an order of magnitude greater current capability with the edge emitter than with a cone emitter. Finite element modeling (FEM) analysis shows that the mechanical stability of the device, under electrostatic loading, is quite good and that we should expect little (~10Å) electrode deflection during device operation. More details of the modeling effort are presented in the Quarterly Technical Report for this reporting period.

Plans for Next Reporting Period

- Complete testing of first triode fabrication run.
- Complete fabrication of diode array test mask. Demonstrate current emission of 5 mA total current.
- Complete fabrication of the second triode fabrication run. Demonstrate current emission from the edge emitter triode.
- Complete high frequency test set-up in vacuum test set-up.
- Initiate high frequency testing and demonstrate 1GHz modulation of an edge emitter triode.

IV. Fiscal Status



Expenditures this quarter	$ 340,492
Total expenditures to date	$1,000,896
Projected expenditures:	
10/92 - 12/92	$245K
1/93 - 3/93	$ 70K
Total Projected Cost for FY92	$1,000,896
Total Projected Cost for Baseline Program	$1,315,650

V. Problem Areas

No main technical barrier or administrative problems are seen at this point.

VI. Visits and Technical Presentations

- A paper entitled "Thin-film edge emitter array vacuum transistor" was presented at the Fifth International Vacuum Microelectronics Conference in Vienna, Austria, July 13-17, 1992, by Dr. Tayo Akinwande. This work was sponsored, in part, by the DARPA VME program. Acknowledgement was given to DARPA.
- Our paper entitled "Nanometer Scale Thin-Film-Edge Emitter Devices with High Current Density Characteristics" was accepted for the International Electron Devices Meeting (IEDM) to be held in San Francisco in December. Approval has been given by DARPA to present this paper.